AIRCRAFT ACCIDENT REPORT 9/83

Accidents Investigation Branch

Department of Transport

Report on the accident to Sikorsky S-76A Spirit G-BGXY at South Kirkton, Aberdeenshire on 12 March 1981

LONDON
HER MAJESTY'S STATIONERY OFFICE

List of Aircraft Accident Reports issued by AIB in 1983/1984

No	*Short Title*	*Date of Publication*
6/82	Lockheed Jetstar 1329–N267L Luton International Airport March 1981	January 1983
7/82	Britten–Norman Islander BN2A G–BBRP Netheravon Aerodrome Wiltshire February 1982	February 1983
8/82	Agusta Bell 206 B Jetranger G–BEKH Dundee Scotland December 1980	April 1983
9/82	British Airways Trident G–AWZT Inex Adria DC9 YU–AJR Zagreb Yugoslavia September 1976	June 1983
10/82	Bell 212 G–BIJF in the North Sea SE of the Dunlin Alpha platform August 1981	April 1983
1/83	Wasp Falcon IV Powered Hang Glider Wittenham Clumps nr Didcot May 1978	May 1983
2/83	Britten–Norman Islander G–BDNP St Andrew Guernsey Channel Islands September 1981	September 1983
3/83	Scheibe SF 28A G–BBGA Enstone Airfield Oxfordshire May 1982	September 1983
4/83	Westland Wessex 60 G–ASWI 12 miles ENE of Bacton Norfolk August 1981	November 1983
5/83	BAe HS 748 G–ASPL Nailstone Leicestershire June 1981	February 1984

No	*Short Title*	*Date of Publication*
6/83	Embraer Bandeirante G–OAIR Hatton nr Peterhead Scotland November 1982	January 1984
7/83	Sikorsky S–76A G–BNSH Aberdeen Airport October 1981	
8/83	DHC–6 Twin Otter 310 G–STUD Flotta Aerodrome Orkney April 1983	
9/83	Sikorsky S–76A Spirit G–BGXY South Kirkton Aberdeenshire March 1981	

Department of Transport
Accidents Investigation Branch
Bramshot
Fleet
Aldershot
Hants GU13 8RX

20 March 1984

The Rt Honourable Nicholas Ridley
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr K P R Smart, an Inspector of Accidents, on the circumstances of the accident to Sikorsky S–76A Spirit G–BGXY which occurred at South Kirkton, Aberdeenshire on 12 March 1981.

I have the honour to be
Sir
Your obedient Servant

G C WILKINSON
Chief Inspector of Accidents

Contents

Accidents Investigation Branch

Aircraft Accident Report No. 9/83
(EW/C739)

Operator:	Bristow Helicopters Ltd
Aircraft:	
Type:	Sikorsky S–76A Spirit
Nationality:	United Kingdom
Registration:	G–BGXY
Place of Accident:	South Kirkton, Aberdeenshire Latitude 57° 33'N Longitude 001° 49'W
Date and time:	12 March 1981 at about 1512 hrs.
	All times in this report are GMT

Synopsis

The accident was notified to the Accidents Investigation Branch by Bristow Helicopters Ltd at 1540 hours on 12 March 1981.

An investigation was begun on-site on the morning of the 13 March 1981. The investigation was conducted by a team including representatives of the Civil Aviation Authority and Bristow Helicopters Ltd. A United States Accredited Representative was appointed by the National Transportation Safety Board, Washington and assisted by representatives of the Federal Aviation Administration and Sikorsky Aircraft.

The aircraft was on a training flight carrying two crew and two passengers. While in straight and level cruising flight in VMC conditions at 3,000 feet one main rotor blade detached. The helicopter then broke up and crashed onto open farmland, all on board were killed.

The report concludes that the blade detached through failure, in fatigue, of the blade root spindle and that failure had been induced by the effects of increased spindle loading and reduced spindle fatigue strength. The former was caused principally by wear in a dry-lubricated bearing, the latter by a production deburring process which differed from the fatigue test standard.

1. Factual Information

1.1 History of the Flight

G–BGXY was allocated to Bristow Helicopters Ltd's (BHL) S–76A Chief Type Training Captain for training flights during the day of 12 March 1981, and he flew two instrument training flights that day prior to the accident flight. The first flight was from 1055 hrs, and was made with the same pilot under training as on the accident flight. The second was from 1155 hrs to 1300 hrs and was made with a different pilot under training. On landing from this flight the Commander reported that he had experienced a severe feed back through the controls, apparently associated with all channels of the No 1 and the No 2 Automatic Flight Control System (AFCS). After fault analysis he had found that the symptoms disappeared when the main AC generator was switched off leaving the inverter to supply the aircraft's AC services, and the rest of the flight was without incident. The BHL engineering department changed the generator control unit and the aircraft's technical log was stamped to call for a flight test. The commander agreed to perform this test on the next flight.

This flight was to be another instrument training sortie involving a flight to the Scotstown Head non-directional beacon (NDB) SHD, a practice NDB let down at Longside Airfield, then on to Banff before returning to Aberdeen Airport. Instrument flight screens remained fitted in the starboard pilot's position, as they had been for the previous flights. Shortly before the aircraft was due to start-up the Commander was asked whether he could take along two passengers who were the brother and a friend of a BHL employee, and he agreed to do so. The crew and passengers boarded the aircraft at about 1435 hrs. After the rotors had been engaged the Commander passed a message via the BHL Ramp Controller on the company frequency of 123.45 MHz to the effect that he had carried out the AC generator test, and that it was still defective, but that he would be willing to fly the sortie if the BHL Line Supervisor who had supervised the rectification work was agreeable. The Line Supervisor passed a message back saying no other aircraft was available and raising no objections to the Commander's proposal. The Commander then replied that he would carry on with the flight.

G–BGXY taxied out just after 1446 hrs and between 1451 and 1456 hrs carried out about 5 practice engine failures after take-off ('rejects') on runway 17. At 1457 hrs XY was cleared for take-off on its instrument training flight and proceeded en route for the Scotstown Head NDB.

By 1504.30 hrs XY was at 4,500 feet and in contact with the North Sea Offshore Radar Advisory Service on 121.25 MHz and at that time passed a revised ETA for Scotstown Head of 1514 hrs. At 1509.45 hrs XY reported five miles to go to Scotstown Head and obtained permission to descend to 3,000 feet. At 1511.47 hrs the Offshore Controller received and acknowledged the message "Offshore X-ray Yankee levelling at 3,000 feet". No further calls were heard from XY on this frequency.

Towards the end of its flight XY was also in contact with Longside Airfield on its Air/Ground frequency of 123.05 MHz. At about 1508.30 hrs XY requested permission to carry out an NDB training approach to Longside Airfield. The last message received by Longside from XY was at about 1510.30 hrs when it confirmed the intention to carry out an NDB approach.

At about 1512 hrs eye witnesses on the ground in the area of St Fergus, Aberdeenshire, saw the helicopter flying apparently straight and level in visual meteorological conditions and then heard a sharp report and saw the helicopter break-up in the air. A few witnesses described seeing a long thin object become detached from the helicopter as the first event, followed by the break-up of the helicopter. Some described hearing a blade slapping noise for a very short period during the break-up sequence. This noise and the sharp report was also heard by other persons in the area who then looked up and saw the helicopter crashing.

The separate portions of the helicopter crashed onto open farmland. All four persons on board were killed.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	2	2	–
Serious	–	–	–
Minor/none	–	–	–

1.3 Damage to aircraft

The aircraft was destroyed by the airborne break-up, ground impact and subsequent fire.

1.4 Other damage

There was some fuel contamination of the farmland in the vicinity of the accident site, but no other damage.

1.5 Personnel information

1.5.1 Commander:	Male, aged 34.
Licence:	Airline Transport Pilot's Licence/Helicopters and Gyroplanes, valid until 17 April 1990, endorsed for the Sikorsky S–76A type as pilot in command.
Instrument rating:	Last renewal test on 29 August 1980.
Medical certificate:	Last medical on 24 February 1981, Class 1, no restrictions.
Competency checks:	Last certificate of test on 27 November 1980.

	Total pilot hours:	Approximately 5,100.
	Total hours on S–76A:	402.
	Total hours in last 28 days:	25.
1.5.2	*Pilot under training:*	Male aged 31.
	Licence:	Airline Transport Pilot's Licence/Helicopters, valid until 2 September 1989, endorsed for the Sikorsky S–76A type as pilot in command.
	Instrument rating:	Initial issue on 26 January 1981, on the Sikorsky S–61N type.
	Medical certificate:	Last medical on 11 February 1981, Class 1, no restrictions.
	Competency check:	Last certificate of test on 5 March 1981 on the S–76A type.
	Total pilot hours:	2,152.
	Total hours on type:	8.
	Total hours in last 28 days:	16.

1.6 Aircraft information

1.6.1 Leading particulars

Manufacturer:	Sikorsky Aircraft.
Aircraft Type:	Sikorsky S–76A Spirit.
Engines:	Two Detroit Diesel Allison 250–C30.
Manufacturers Serial No:	760021.
Date of manufacture:	September 1979.
Certificate of Registration:	Issued in name of Bristow Helicopters Ltd on 6 November 1979.
Certificate of Airworthiness:	Transport Category (Passenger) valid until 18 December 1981.
Total Hours – Airframe	1171.40 hrs.
Total hours main rotor blade Spindle (black):	1247.10 hrs.

Certificate of Maintenance:	Valid until 1210.40 airframe hours or 16 March 1981.
Last check:	50 hr check at 1150.15 airframe hours on 4 March 1981.
Fuel:	Prior to flight the aircraft had been refuelled with Jet A1 fuel to give total contents of 281 United States gallons.
Maximum authorised weight:	10,000 lbs.
Despatch weight:	9,483 lbs.
Estimated accident weight:	9,283 lbs.
Centre of gravity ranges:	Fwd limit: 197 ins aft of datum at 10,000 lb increasing linearly to 193 ins aft at 8,500 lbs. Aft limit: 206 ins aft of datum at 10,000 lb increasing linearly to 210 ins aft at 8,750 lbs.
Centre of Gravity at Despatch:	201.4 ins aft of datum.
Estimated centre of gravity at accident:	201.0 ins aft of datum.

1.7 Meteorological information

An aftercast of the weather for the area and time of the accident obtained from the Meteorological Office, Bracknell, was as follows:

General situation:	An unstable south westerly airstream covered Scotland.
Winds and temperatures:	2,000 ft 230 15 knots +6 C 5,000 ft 240 15 knots 0 C
Cloud:	Broken strato-cumulus base 2,500 feet tops 6,000 feet, but in any showers base 2,000 feet tops 8,000 feet.
Surface visibility:	30 kms or more but 9 kms in any showers.
Weather:	Scattered showers.

The captain of a helicopter operating in the crash area at 1530 hrs stated that visibility was over 30 kms, cloud was 4 oktas strato-cumulus base 3 to 4,000 feet, and there was no precipitation.

1.8 **Aids to navigation**

The aircraft was homing to the Scotstown Head non-directional beacon 'SHD' at the time of the accident.

1.9 **Communications**

Radio-telephony recordings were available for all communications between G–BGXY and Aberdeen Airport during the flight. G–BGXY first contacted Aberdeen Ground Movement Control on 121.7 MHz at 1443 hrs, and on transfer to Aberdeen Tower on 118.1 MHz at 1450 hrs requested permission 'to do about five rejects before departing for Scotstown Head'. Shortly after this Aberdeen Tower cleared XY to carry out 'rejects' (practice single engine failures on take-off) on runway 17. At 1456.30 hrs XY reported that the rejects had been completed and was then given a clearance to take-off on runway 17 and then turn left onto 120°. At 1458.45 hrs XY was transferred to Aberdeen Approach/Radar on 120.40 MHz. At 1500.30 hrs XY was instructed 'Turn left now direct to Scotstown' and at 1501.30 hrs reported level at 4,500 feet (on the Aberdeen QNH). At 1502.30 hrs XY was transferred to the North Sea Offshore Sector Radar Advisory Service on 121.25 MHz. At 1504.30 hrs XY passed an ETA for Scotstown Head of '14', and at 1509.45 hrs reported five miles to go to Scotstown Head and obtained permission to descend to 3,000 feet. At 1511.47 hrs the ATC controller received and acknowledged the message 'Offshore X-ray yankee levelling at three thousand feet'. No further calls were received from XY on 121.25 MHz although the aircraft was called from 1515.10 hrs after a report of a crash had been received.

Towards the end of the flight XY was also in contact with Longside Airfield on its Air/Ground frequency of 123.05 MHz. No radio-telephony recordings were available for this frequency. At about 1508.30 hrs XY contacted Longside and said that it was en route from Aberdeen to Point Bravo (Banff) via the Scotstown Head NDB, and requested an NDB training approach into Longside Airfield. The last message received by Longside from XY was at about 1510.30 hrs when XY confirmed that it would like to carry out the NDB approach. At about 1513.30 hrs the Longside radio operator was told that smoke had been sighted in the Scotstown Head direction and he then called XY several times but received no reply.

1.10 **Aerodrome and ground facilities**

Not applicable.

1.11 **Flight recorders**

The aircraft was not equipped with a flight data recorder or a cockpit voice recorder, nor were these required to be fitted.

1.12 **Wreckage and impact information**

1.12.1 Accident site details

The wreckage of G–BGXY fell on open farmland 6 km north, north-west of Peterhead, Aberdeenshire, Scotland and 1.5 km south of the Scotstown Head beacon.

The items of wreckage had descended separately, the large items showing evidence of almost vertical descents, and it was evident that the aircraft had broken up in mid-air. Most of the wreckage was contained within an area approximately 400 metres by 400 metres generally to the west and south of the impact point of the cabin section (see Figure 1). One item, a main rotor blade, colour coded as black, had landed widely separated from the rest of the wreckage at a position 1100 metres directly south of the cabin impact point. This blade and its impact information will be described separately below.

The cabin impact area contained debris from the complete forward fuselage and included the engines. The forward fuselage impact had been essentially vertical and the wreckage remained in or alongside the resulting crater. The cabin section had suffered complete disruption at impact and had subsequently been consumed by fire. The area immediately surrounding the crater had contained, in almost correct relative position, nose structure, flight instrumentation, seats and the engines. The engine bay fairing lay nearby. Flying control components, which are normally positioned on the cabin roof in front of the main gearbox, were also collected from this restricted area. All four passenger doors, or parts thereof, and both baggage compartment doors were identified at the cabin impact or within the general wreckage area.

The occupants of the helicopter had been found in or near the cabin wreckage along with a number of ballast bags which were being carried. The engine bay, still containing the engines, had been badly damaged by impact and fire but neither engine showed any evidence of explosive rupture or burn through. The fuselage top fairings, with two exceptions, were all recovered in the general wreckage area. Only the rear portion of the front cowling section was found and the starboard main gearbox side panel was not identified. None of the recovered cowls nor the dorsal fairing covering the tail rotor drive shaft on the tailcone showed any evidence of contact with any of the rotating blades.

The tailcone, complete with tail rotor assembly, had detached from the helicopter at the joint line with the cabin and lay 300 metres southwest of the cabin impact. Two blades were still attached to the tail rotor hub and two lay separated nearby. A lengthwise rip had been caused on the starboard side of the tailcone by the tail rotor control cables which had subsequently failed in tension. Otherwise the tailcone had been complete prior to impact and all other damage appeared to be due to ground impact.

The main gearbox and rotorhead (see Figure 2) lay 300 metres south of the cabin deeply embedded in the ground from a vertical impact.

The gearbox, with the rotorhead had detached from the airframe in the air at its 4 mounting points. All the failures were in overload.

The top bifilar assembly was not recovered but, though its condition could not be determined, its mode of detachment was that of instantaneous overload in the mating section between the upper and lower bifilars and there was no sign of a pre-existing defect in that failure.

The lower bifilar had become detached from the rotor head at ground impact and was recovered with the head and gearbox. All damage to the bifilar appeared to be related to the ground impact.

Three of the four main rotor blades coded blue, red and yellow were also in the main wreckage area. The blue and red blades had become detached through failure of their blade root attachments (spindle/cuff, P/N 76102–08001–041). These had failed through overload, with bending being evident in the mode of failure and in the damage sustained by the spindles and the rims of the elastomeric main blade flap/drag bearings. The yellow blade fitting also showed evidence of violent blade movements but the blade had become detached through failure of the graphite composite material at the blade root.

The black blade was separated by approximately 800 metres from any other wreckage directly south of the cabin impact point in a field of short grass. The blade had detached through failure of the blade root attachment spindle. The spindle had fractured at its extreme inboard end within the thread which engages the single retention nut. Examination of the fracture revealed indications of fatigue. The spindle was removed from the blade for detailed examination described later.

The black blade was undamaged apart from scuffing apparently sustained on impact and a section of honeycomb trailing edge, about 0.7 metres long, missing at about mid-span. This portion of the blade was found, as a single piece, in the main wreckage area. There was no extraneous damage associated with the detachment of this portion of trailing edge.

1.12.2 Initial Examination of the Main Blade Retention Assemblies

The gearbox and rotor head were recovered from the site and removed to the operators facility for examination together with the blade spindles (see figure 3).

The spindles were manufactured from a forged titanium alloy (Ti–6AL/4V). The main retention thread at the inboard end of each spindle, which, in the case of the black spindle, contained the observed fatigue fracture, had been formed by a machining (cutting) process.

The black spindle, which had the previously noted fatigue damage in its failure at the inboard end, was otherwise undamaged (see Figure 4). The inner race of the dry lubricated shear bearing (see Figure 5) exhibited distinct circumferential grooving (labelled 'phonograph grooving') on its surface which was, none-the-less, highly polished. The 'Teflon' outer race, contained within the elastomeric bearing assembly also had a grooved appearance matching that of the inner race surface. Some 'Teflon' had been removed in the aft lower quadrant by the passage of the splines on the inboard end of the spindle as the blade detached in flight. The external surface of the conical elastomeric element (see Figure 6) had also received slight impact damage in line with the 'Teflon'. It appeared that prior to the removal of some 'Teflon' by the outward passage of the spindle, the complete outer race surface had been covered by the 'Teflon' coating.

The main rotor blades are colour coded as follows: clockwise from above, Black, Yellow, Blue and Red.

The yellow blade root spindle, together with a remaining stub of the blade itself was still attached within its blade retention assembly. The spindle, however, was bent and the rim of the elastomeric bearing had sustained damage which also showed that the spindle had been subjected to extreme deflections. The shear bearing inner and outer races were very similar to those from the black assembly with 'phonograph grooving' on both, a full surface coating of teflon but, of course, without the spline damage sustained by the black assembly.

The blue spindle had broken, in virtually rearward bending, at a position immediately outboard of the elastomeric bearing. The outboard lip of the elastomeric assembly had again suffered heavy damage at a number of points around its periphery from contact with the spindle during extreme deflections. The shear bearing inner race surface was again highly polished and grooved. The outer race exhibited grooving and, at its outboard end, in the lower leading quadrant the teflon coating had been worn away exposing the steel surface underneath which had been discoloured by heavy metal-to-metal contact with the inner race. Over an adjacent area the teflon fabric had become detached from the metal surface.

The red spindle had failed immediately outboard of the elastomeric bearing and had heavy spindle contact damage mainly in the rear lower quadrant.

The red shear bearing differed from the others in several respects. The inner race did exhibit polishing and grooving of the surface but only over certain restricted areas of the surface; around the circumference at either end of the contact area with the outer race (the outer race being shorter than the inner) these areas being notably more extensive at inboard top and outboard bottom. The outer race teflon coating appeared quite different in colouring and surface appearance from the other blade assemblies. The surface was a tan colour (the other bearings had a dark brown teflon coating) which faded into a light tan or fawn colour in areas of wear. Visually, the wear appeared most marked around the periphery of the outboard end. In one area in the outboard, lower, rear quadrant the homogeneous top layers of the bearing material had been removed exposing a fabric-like substrate. This area was bounded on its outboard end by a sharply defined stepped edge 7 mm in from the end of the race.

It was ascertained that these bearings had been manufactured by two different specialist suppliers; the red bearing by Kahr Bearings Division of the Sargent Industries Group and the others (black, blue and yellow) by the Fafnir Bearing Company. The two different kinds of bearing had, therefore, been manufactured for this application using different proprietary standards and materials.

Following this examination the diameters of the inner and outer races were measured at various points, the results being tabulated in table 1.

The steel inner races were found to be within .002 inches of drawing dimensions but the teflon outer races all showed marked increases in their internal diameters relative to the drawing requirements. Given the observed surface condition it was assumed that the increase in internal diameter was due to wear (a subsequent inspection of unused bearings confirmed that they complied with drawing dimensions as new). As can be seen the three outer races manufactured by Fafnir Bearing Co exhibited significantly and consistently more wear than the single race manufactured by Kahr. All the outer races showed the maximum wear at the outer end (relative to blade) and in the vertical or near vertical plane. The polishing and 'phonograph' grooving of the inner races was also most extensive and marked at the race ends and in the vertical plane.

1.12.3 *Detailed Examination of the Main Blade Retention Assemblies*

The black main blade retention assembly comprising the two elastomeric bearings, the 'Teflon' shear bearing and the retention nut, with the still engaged, fractured, end of the spindle were returned to the manufacturer for detailed inspection witnessed by AIB and NTSB.

The droop stop mechanism had sustained some damage in the ground impact and the elastomeric was contaminated with mud. The unit was progressively disassembled and examined for evidence of anomalies or distress other than the fracture of the spindle and the damage inflicted as it detached.

The droop stop itself had contact marks which showed that the rotor blade had been in contact with it while the stop was in the high speed running position. (This is consistent with the condition known as 'droop stop pounding').

The outer face of the conical elastomeric bearing had sustained some surface damage from the passage of the broken spindle end but otherwise showed no evidence of damage or deterioration. In particular, there was no sign of extrusion of the rubber from between the steel laminates ('eraser' type failure) and X-ray examination revealed no cracking of the steel laminates themselves. The spring rate of the bearing was measured and found to conform closely to specification.

The main blade retention nut was removed by undoing its four fixing bolts, loosening torques of between 80 and 90 lbs ins were measured (specified assembly torque 125 lbs ins). There was no evidence of marked movement between the nut and the end plate of the thrust bearing though there were some local contact markings evident. The protrusion of the spindle end from the inboard end of the retention nut was measured at between .048 and .051 ins (0.030 and 0.050 ins specified).

The broken spindle end was removed from the retention nut and the nut and spindle threads examined. Contact marking could be seen on the thread pressure faces and there had been some transfer of the anti-galling silver coating from the steel nut to the spindle surface in these areas but these effects were not associated with the origin of the fatigue cracking and are not considered relevant.

Subsequently the spindle thread was sectioned both at the fatigue origin and over a representative portion of thread to enable metallurgical and thread form examinations to take place. The specified thread was 1.625 – 12 UNJ – 3A per MIL – S – 8879 formed by machining with a single point tool. In general the thread form conformed to specification but it was modified by two effects.

The machining process had left circumferential marks on the thread flanks and roots and when the threads were sectioned some variation in contour was visible in the root radius. In the plane of the origin some deviation from a smooth circular form was visible in the root but this was remote from the origin and, at the origin no such deviation was identified.

In addition to the machining marks another type of surface scoring could be distinguished on the thread surface. This was determined to be caused by a deburring process, which employed an abrasive material (No 7440 Brown Medium Type A 'Scotchbrite') mounted as a disc on a rotary power tool. The finishing instructions required this treatment for the thread crowns and run-out but it was evident that here the abrasive had penetrated to the thread flanks and roots.

The deburring marks were distinguishable, generally, from the original machining marks in that they were somewhat random in direction and were relatively short and discontinuous.

The surface condition was compared to two other batches of spindles; the three other spindles from G–BGXY and the spindles used in the fatigue life substantiation program. The 'yellow' and 'red' spindles from G–BGXY showed signs of 'Scotchbrite' scoring in the thread roots but the 'blue' spindle was relatively clear.

The condition of the fatigue test samples, as far as could be determined, varied from cases which appeared to be clear of deburring damage to others that appeared much worse, in terms of random surface scoring, than the subject spindle. It was determined, however, that the deburring process used on the test spindles had employed a rotating steel wire brush and not the 'Scotchbrite' material.

The manufacturer decided that the black assembly, comprising the elastomeric bearing, the 'Teflon' shear bearing and the retention nut, could be test flown with an instrumented spindle. Results from the test flying, which subsequently included all the shear bearings from G–BGXY, are reported in 1.16.1.

The condition of the inner and outer races of the shear bearing in the elastomeric hinge assembly attracted attention during the initial examination of the components from G–BGXY. These components were later examined in some detail by the manufacturers involved. Other information on bearing wear was obtained from the S–76A fleet of aircraft as the operators complied with an alert service bulletin, ASB–76–22A, and relayed the results of required dimensional checks back to the manufacturer (see Figure 7).

When first examined, the bearings from G–BGXY exhibited a certain amount of free dust which had the colour of the dry lubricant material (P.T.F.E. and other constituents). This was considered normal for this sort of bearing. There was no other gross contamination by any foreign material evident. Examination by electron-microscopy and energy dispersive X-ray spectroscopy identified some contaminating particles embedded in the fabric liner. Though it was considered that the amount of contamination seen on the microscope scale could be a significant factor in increasing the wear rate there was no single dominating contaminent foreign to the bearing or the spindle assembly. The most common contaminents were Iron and Chromium, the main constituents of the stainless steel of the bearing inner race. These materials in a free state were more likely to have been, initially at any rate, the product of a high wear rate than the cause. It had to be remembered, in considering contamination as a factor in the wear behaviour of these bearings that the surfaces are not sealed from the atmosphere and also that the whole assembly had been buried to some depth in soft soil by its impact. Further, while all four bearings had been subjected to the same service environment, three, of one manufacture, showed markedly worse wear than the fourth of a different manufacture.

The bearing manufacturer, in the case of the Fafnir bearings, considered that the wear observed at both ends of the bearing had been caused by load concentrations arising from 'misalignment' and that this had been a significant factor in accelerating the wear rate.

1.12.4 *Metallurgical Examination of the Black Blade Spindle*

The inboard end of the black spindle, contained within its retention nut in the bearing assembly, was taken to the manufacturer's Materials Engineering Laboratory in the USA with AIB and NTSB in attendance and the fracture face on that portion of the spindle was the subject of metallurgical examination by the manufacturer. The major (outboard) part of the spindle was retained in the UK for independent material and fractographic analysis by the Materials department of the Royal Aircraft Establishment, Farnborough.

Titanium alloy samples taken from the black spindle were found to conform to the required specification in terms of their chemical composition and mechanical properties.

As can be seen from Figure 8 the fatigue fracture occupied a sector of the cross section initiating at the underside aft surface (with respect to blade movement) and developing to a crack front which intersected the internal bore of the spindle and was parallel with the 'horizontal' plane of the spindle. The area of fatigue was measured as 34% of the cross section.

Within the fatigue area a number of separate fatigue origins were identified. The forward origin, designated as the principal origin, was the one which had developed to ultimate failure. Its circumferential position was approximately 30 degrees aft of the spindle bottom centre. The designation of one of the origins as the 'principal' origin does not necessarily imply that it was the first in the sequence of origins but merely that it was the one which gave rise to the dominant area of fatigue.

The plane of the fatigue fracture was initially in the spindle thread root inboard of the first thread of the blade retention nut. The single incomplete nut thread outboard had been partially removed by shearing when the spindle became detached.

The principal origin lay in the root radius near its transition to the flank of the next inboard thread. It was located in a surface score which was typical of those demonstrated to have been caused by the production deburring process using 'Scotchbrite' abrasive pads. The secondary origins also appeared to be variously located at 'Scotchbrite' scores and machining marks, though a clear differentiation could not always be made between these features.

From the fracture cross section (Figure 9) it can be seen that, at initiation, the plane of the principal fatigue was perpendicular to the local thread root surface. As the crack penetrated deeper into the cross-section its plane changed so that, though it became perpendicular to the spindle axis in the radial direction, transversely it adopted an angle steeper than that of the thread helix.

The principal origins development in a forward direction (blade advancing) was faster than in the aft direction so that at final rupture the crack front had turned in direction from 30° to the spindle horizontal to parallel with the spindle horizontal. In the forward direction the crack tip followed the thread root while in the aft direction the development appeared more complex with the existence of the secondary origins and an observed tendency of all the cracks to progress up the thread flank at their tips.

Expert interpretation of the observed surface features at the microscopic scale differed, but the fracture was agreed to be representative of 'high cycle' fatigue and the manufacturer estimated there to be 330,000 striations from origin to rupture across the principal fatigue. The manufacturer also assessed the secondary fatigues as being of slightly faster growth rate, at a given penetration, than the principal until they were overtaken by it.

Striation counts were also available, for comparison, from four test rig spindle failures obtained during certification testing and from the one previous in-flight failure. The cyclic loading in two of the test rig failures was approximately equivalent to the aircraft's measured major 'Ground-Air-Ground' (GAG) cycle and in another case equivalent to the highest of the fatigue damaging flight loads experienced transiently during manoeuvres.

These rig results, of course, resulted from the repeated application of a single load cycle whereas the subject failure had been the result of a spectrum of fatigue damaging loads from a varying flight routine, with different loads becoming effective as the crack progressed. These results do, however, differentiate this failure from the previous in-flight failure (approx 60,000 striations) and, assuming spindle material properties to be similar, give an indication of the magnitude of the loads sustained by the spindle. The results suggest that the subject failure was associated with 'high cycle' fatigue (flight loads) rather than 'low cycle' fatigue (GAG loads).

Numerous crack front progression markings were visible on the surface of the primary fatigue fracture. Between 48 and 53 separate bands could be identified of varying clarity and definition. The lack of definition of the banding together with the asymmetry of the fracture's development and the difficulty of identifying and counting striations in the two-phase crystal structure of Ti-6A1-4V made any close correlation with the known flight history of the aircraft impracticable. The banding is however, presumed to be the result of a repetitive flight condition; individual flights or peak flight loads recurring within these flights. Assuming the latter case and a damaging load cycle with every rotor revolution then the striation count of 330,000 would indicate a minimum crack growth time of 19 hours. The more probable interpretation of the banding, as representing individual flights with only some of the higher flight loads being damaging, would give a crack growth time, when the recorded flight times are considered, of between 51 and 64 hours. The situation, of course, is complex in that some flights included a 'rotors-running' turn round, imposing a minor GAG load cycle and, also, flight load intensity would vary with aircraft loading and manoeuvres, lesser loads becoming damaging as the crack propagated.

1.13 Medical and pathological information

A post mortem examination established that all four occupants died from multiple injuries consistent with a high speed impact. There was no pathological evidence of a causitive or contributory medical factor in the accident.

1.14 Fire

The evidence of fire was confined to the ground and the wreckage in the area of the cabin impact. No other wreckage showed signs of fire and no evidence of fire in the air was found.

1.15 Survival aspects

This was a non-survivable accident.

1.16 Tests and Research

1.16.1 Flight Testing

The manufacturer undertook to carry out a flight test programme to obtain in-flight measurement of stress in the blade root spindle with a variety of shear bearing wear conditions simulated and, specifically, with the worn shear bearing and elastomeric bearing from the 'black' blade of G–BGXY.

The flight tests, sixteen in all, were intended to provide data at all the flight conditions and manoeuvres seen in normal operation in order that the original flight 'spectrum', on which the fatigue life of the spindle was based, could be reassessed.

Running concurrently with the flight test programme a survey of operator usage was conducted by the manufacturer. The survey included such factors as prolonged low temperature operation, incidence of severe icing and droop stop pounding. The results of the survey were used for comparison with the usage assumed by the manufacturer in the spindle life calculation.

The flight test spindles were instrumented with straingauges as shown in Figure 10. Additional rotor and airframe instrumentation recorded flight conditions and other loadings on the rotor system.

The flight test results demonstrated that spindle stresses inboard of the shear bearing varied directly with main rotor shaft bending moment which, for a given rotor speed and loading is a direct indication of blade flapping angle. They also increased progressively, with diametral gap in the shear bearing.

It was seen, also, that the torsion sustained by the spindle inboard of the pitch change arm was not carried into the elastomeric thrust bearing by the spline immediately outboard of the thread, as had been intended, but was carried into the thrust bearing by the blade retention nut. A torsional load was therefore additive to the bending and tensile loads though its phase was considered to be at almost 90° to that of the resultant (of bending moment and centrifugal) tensile load and therefore the peak tensile load virtually coincided with the minimum torsion load. The manufacturer considered, from these results, that spindle stresses in the thread and relieving groove were not appreciably increased by the torsional component.

The flight results otherwise, neglecting the effects of bearing wear and torsion, showed that, while there were differences in the incidence of different manoeuvres and time spent at specific flight conditions, when usage was translated into fatigue damage, the usage assumed in certification of the spindle was more severe than that actually experienced in operation. The results also showed that conditions such as blade icing, droop stop pounding, control and damper bearing wear and low ambient temperature did not by themselves produce significant fatigue loading in the spindle thread.

1.16.2 Spindle Fatigue Rig and Small Scale Coupon Tests

The manufacturer carried out a fatigue rig programme of investigation using both full size spindles and small scale notched test coupons. The use of small coupons permitted sample numbers high enough to give results which were statistically significant in terms of mean values and scatter. Though the coupons were notched to give a stress concentration factor of 3.5, the assumed value in the spindle thread, the results were not taken to be absolutely representative of spindle fatigue strength but were used for a comparative evaluation of the effects of the variables being considered. Though a number of different variables were considered in the full size spindle tests the sample sizes were in some cases too small to give statistically meaningful results. Where the sample size was large enough the full size tests did give a practical indication of mean fatigue strength from which anticipated fatigue lives could be calculated.

1.16.2.1 Small Scale Coupon Tests

The test coupons were cut from the spindle shank area immediately outboard of the locating spline on spindles returned from service. The material was thus representative of the forged condition existing in production spindles near the area of failure. The coupons were of circular cross-section, with a circumferential notch and were tested under purely axial loading. A steady load of 25 KSI was applied to represent the steady load level in actual spindles.

The notch was subjected to finishing treatments representing the thread surface. A batch of coupons in the as-machined condition was taken as a datum. A further batch was subjected to the 'Scotchbrite' deburring process and certain sample batches from both conditions were stress relieved in order to give an understanding of the influence of residual surface stresses on the failure mechanism.

The results of the tests are shown in Table 2.

These showed a marked reduction in mean relative fatigue strength following Scotchbriting and stress relieving.

1.16.2.2 Spindle Fatigue Rig Tests

The straingauge positions adopted for both the flight tests and the full-scale fatigue rig tests are shown in Figure 10. The stations designated as '1' and '2', inboard and outboard of the shear bearing respectively, were established positions on accessible, parallel section parts of the spindle which had been previously used during certification in both rig and flight tests. Results from these positions could therefore be correlated between the tests carried out during the accident investigation and those carried out for certification. For the accident investigation programme instrumentation at a further position was developed, denominated '1A'. Position '1A' lay in the stress relieving groove immediately outboard of the spindle thread and presented technical problems for the application of straingauges in a restricted space and on a surface with double curvature. Miniature straingauges measuring total stress (4) and torsional stress (2) were successfully fitted, however, and flight and rig measurements obtained. The fatigue rig which was used allowed the application of torsion to the test spindle as well as axial and bending loads. Vibratory bending and torsional loads when included were applied in phase to obtain the 'worst case'. Bending was applied in only one plane, representing a resultant of flapwise and edgewise loadings. All tests were run with a standard steady axial load representing 107% main rotor speed (NR).

The full scale fatigue tests were carried out on 23 spindles most of which had been returned after some service usage. The manufacturer considered that where spindles had had some service use but had not been affected critically by the 'Scotchbrite' deburring process, then the service lives, up to 1,300 hours for the test specimens, would represent a negligible proportion of their fatigue lives, calculated at over 50,000 hours for non-treated spindles, and would not discernibly affect the test results.

The results obtained allowed an assessment to be made of the 'Scotchbrite' deburring process, of residual stress relief and of additional torsional load. The datum used for comparison in the analysis of this data was the mean of the fatigue substantiation data used for certification.

The results of these tests are shown in Table 3. It should be noted that the load increase due to torsion shown in Table 3 assumes torsion to be in phase with bending.

1.17 Additional Information

1.17.1 Certification of the Main Rotor Blade Retention Assembly

When the Sikorsky S–76A helicopter received its FAA certification in 1979 it involved the first civil certification of an articulated main rotorhead design which used elastomeric hinges to accommodate all blade movement. The rotorhead design had evolved from two previous military types (CH–53A and UH–60A Blackhawk). The S–76A rotorhead was closely similar in its components and layout (see Figure 2) to that of the UH–60A Blackhawk.

The system loading was obtained from ground and flight testing of the rotor assembly and rig tests were carried out to establish the fatigue or endurance characteristics of the individual components (blade root spindle/cuff, elastomeric elements, retention nut etc). Such testing was carried out in accordance with an approved Test Programme Plan to conform with Paragraph 29.571 of US Federal Airworthiness Regulation No 29.

Two particular components in the main rotor blade retention assembly, the dry-lubricated 'shear' bearing and the spindle/cuff, were of special interest in the accident investigation and the testing and certification process, as it affected these components is considered in detail.

In the proposed programme for certification of the main rotor blade retention assembly which was submitted by the manufacturer, accepted by the US Federal Aviation Administration and ultimately accomplished by the manufacturer, the shear bearing was not included amongst the individual components considered for testing to establish their integrity and durability.

The CAA considered the aircraft for certification in the UK under the reciprocal agreement with the United States under which FAA certification of compliance with the provisions of the Federal Aviation regulations, where similar in effect to the application of UK standards, is taken as a basis for UK acceptance. In particular cases, where such similarity is known or found not to exist, additional requirements may be imposed by the CAA. For the certification of the S–76A the CAA instituted a survey of the design and did introduce a number of additional requirements but none affected the shear bearing or the spindle/cuff assembly.

1.17.1.1 Pre-Certification Testing of the Shear Bearing

When considering the selection of specialist suppliers of the Sikorsky designed shear bearing in the main blade retention assembly, the aircraft manufacturer invited a large number of bearing manufacturers to submit sample dry-lubricated bearings for comparative testing.

The bearing materials supplied were tested to a US Military Specification, MIL–B–81819, for 'Bearings, Plain, Self-lubricating, Self-aligning, High-Speed Oscillation' and were supplied in the geometrical form defined in that specification ie spherical. The bearing materials involved were the proprietary products of the supplying companies and, being of different material composition and production methods, could be expected to behave differently in a given application. There was no standardised comparative test available for self-lubricated cylindrical bearings. Nor were there any published standardised tests available for assessing a bearing materials' performance when subjected to the load concentrations that develop in a cylindrical bearing sustaining bending moment loads as well as symmetrical transverse loads. It appears, however, that MIL–B–81819 was taken, in the first instance, as being a suitable comparative test for the bearing materials in the main rotor blade retention assembly shear bearing. Following the assessment, three bearing manufacturers were given the opportunity to supply bearings for the S–76A and two, Fafnir and Kahr, accepted.

The bearings then supplied, to the Sikorsky design and a single Sikorsky part number, formed part of the assemblies used and tested during the pre-certification rig and flight testing. Total flight testing amounted to 1,200 hours (3 aircraft) and additional ground testing on a whirl rig and ground test vehicle amounted to 444 hours. No systematic data, categorised by manufacturer, is available concerning behaviour of the shear bearings during this testing and it is evident that individual bearings saw only a limited service time of a few hundred hours. Reportedly, these bearings suffered no noticeable wear.

Individual bearings were subjected to much longer periods of service during endurance and fatigue rig tests of the main blade retention assembly. In particular, four different bearings, of unknown manufacture, were subjected to 2,000 hours of high cyclic loading during tests of the elastomeric hinges, again reportedly suffering no significant wear. However, these rig tests, which were carried out in a laboratory environment, did not include a representative application of torsional loads or movements, thus significant elements in the wear process for the shear bearing were missing.

From the test experience and from service experience with the Blackhawk military helicopter, which has a rotor head of similar design and bearings designated to the same loading criteria, it was considered that the bearings would probably give a service life of approximately 2,000 hours. At certification, no life was ascribed to the bearing and no particular inspection requirement laid down for it. Inspection of two 'fleet leader' rotor heads, when they had completed 1,000 hours of service, reportedly showed all shear bearings to be within drawing requirements, i.e. their wear had been negligible. Again, the manufacturer of these bearings is not known.

The standard of blade instrumentation employed during the certification flight and ground testing was such as would have detected high stresses at the inboard end of the spindle (inboard of the shear bearing). Measurements of spindle stress taken for the purpose of calculating spindle fatigue life are, in comparison with those taken during the accident investigation, consistent with bearing diametral gap being within drawing limits during the flights in which those measurements were made. No flight or ground tests were carried out with simulated wear of the outer race of the shear bearing.

1.17.1.2 Certification Testing of the Spindle/Cuff

Full scale fatigue rig testing of six spindles was carried out to confirm a mean or 'baseline' 'S/N' curve (stress VS no of cycles to crack initiation) for certification of the spindle as a 'lifed' component. Use of this rig data to certificate the spindle for a declared fatigue life is described below.

The fatigue rig subjected each test spindle, as part of a blade retention assembly, to a steady axial load (representing 107% NR) and to a vibratory bending load equivalent to combined axial and bending vibratory loads. Straingauges were placed at the stations shown in Figure 10. The manufacturer anticipated that fatigue failure would occur in the spindle thread and as the critical area was inboard of the spline which was designed to react torsion, no torsional loads were applied to the test spindles.

The applied axial loads were measured directly and the bending moments calculated from straingauge measurements. The combined axial and bending vibratory loads were converted to a vibratory bending moment at the reference plane corresponding to spindle station 1. It was this load or stress parameter which was plotted in combination with the flight data for the same station, to give the fatigue curve from which life calculations were made (see Figure 11.)

Four spindles were tested to failure with cracks developing as expected through the spindle thread. The other two spindles had not developed cracks at the end of the planned test. Test spindles were variously of prototype or production standards which were identical in shank and thread areas. None had been subjected to the production deburring process with the 'Scotchbrite' material. Some had been deburred with a rotating wire brush and, when examined during the accident investigation they appeared to have sustained damage in some thread roots which was visually more severe than that seen on the accident spindle.

Though the reference plane for which the loads were calculated for the fatigue life determination was not that at which test spindles had failed, the manufacturer decided that it was the nearest practicable point at which straingauge measurements could be taken. Its simple parallel section geometry also allowed reliable assumptions to be made about the relationship of applied loads and resultant stresses in that plane.

The failures on test had occurred in the threaded end of the spindle at the point of its engagement in the retention nut. The plane of failure was separated from the reference plane by the spline which was designed to perform as a locating device for the spindle in the elastomeric bearing assembly and to transmit torsional loads from the spindle to the thrust bearing. The 'Teflon' bearing in the elastomeric assembly was expected to partially absorb spindle shear and bending loads resulting from the blade edgewise and flapwise angular movement and the spring rate of the elastomeric hinge. Except for the reduction in stress with the removal of torsion by the spline, the stress in the failure plane was expected to have a direct and close relationship to that in the reference plane.

The failures had occurred at a position of stress concentration (with an assumed KT of 3.5) but although the actual stresses at the failure plane may locally have been much higher than at −1 as they were believed to have a direct and understood relationship to those at −1 it was assumed that they (expressed as an equivalent moment) could be used as the criterion for calculating a fatigue life. As full scale fatigue tests were carried out to establish a load versus crack initiation time the stress concentration factor did not have to be considered separately as it was accounted for in the actual rig test results obtained.

The data points obtained from the certification testing were used to define a mean curve of load versus cycles to failure. The points themselves represented only a limited portion of the range of loads which had to be considered for a service part and contained a degree of experimental scatter in the results. A standard curve shape, for the Titanium alloy (Ti–6A1–4V) was fitted statistically to the results. This process allowed an extrapolation of the data further into the high cycle range, allowing an estimate of the endurance limit load, and also towards the low cycle range where higher load cycles representing the 'Ground-Air-Ground' cycle were significant.

To allow for scatter in the fatigue strength of production spindles a 'worst case' curve for the spindle was obtained by factoring the mean line obtained from test by 70% of stress at a given number of cycles. For an anticipated scatter criterion (standard deviation) of 10% this line set 3 standard deviations below the mean, should have encompassed 99% of a normally distributed population of spindles of fatigue strength less than the mean.

This boundary was modified by two further considerations. A spindle which had been used in an endurance test on the elastomeric bearing had failed with an apparently low fatigue strength. The manufacturer considered that there were factors which accounted for it being of low strength but they lowered the load versus cycles line to encompass its failure. At the low cycle end of the curve, where the estimated life is less sensitive to the applied load and where no experimental results were available, extra conservatism was introduced in defining the worst case, or working line, by applying a dividing factor of 5:1 to the mean life at a given load.

1.17.2 *Calculation of Spindle Fatigue Life*

The load versus cycles curve, as obtained in 1.17.1 formed the criterion against which the loading measured during the flight tests was considered fatigue damaging and, if damaging, it was used to show how much fatigue damage would be caused in a nominal 100 hours of an anticipated flight usage. From the inverse of this damage figure, a minimum crack initiation time could be calculated. This life was further factored by standard allowances to obtain a service retirement time which was calculated at 50% of the minimum crack initiation time. The flight usage was represented by a spectrum of all measured flight loads and their anticipated frequency of occurrence assembled to represent the most severe fatigue environment likely to be encountered and was referred to as the certification spectrum (see Figure 11).

Following an accident to an S–76A in Brazil in 1980 (see 1.17.3) and before the accident to G–BGXY, the manufacturer had reassessed the original spindle fatigue strength data using a revised curve shape to fit the data points and this effectively up-graded the fatigue strength assessment of the spindle. The company reported that, in their calculations of the effect of bearing wear using this reassessed strength and loads such as would be experienced with an assumed wear rate for the teflon to complete wear-out, a replacement time in excess of 8,000 hours (50% of minimum calculated life) still resulted. Further, assuming the 'Teflon' to be absent from the start, a replacement time of 4,000 hours resulted.

It was apparent therefore that, even with the amount of bearing wear measured on G–BGXY an actual failure at 1,247 hours could not be accounted for with this data and, in any case, the company's assessment of the flight usage to which G–BGXY had been subjected was that it was less severe than the postulated 'certification spectrum' and that there were no unexpected loads arising from unusual conditions in its operation.

An operator's flight spectrum for G–BGXY was devised and fatigue calculations for G–BGXY based on it. A spindle fatigue life assuming full bearing wear (.029 ins gap) present at all times and a mean spindle fatigue strength appropriate to a batch of spindles treated with 'Scotchbrite', gave a calculated time to failure of 47,000 hours. A similar calculation assuming the estimated lowest strength 'Scotchbrite' spindle, however, gave a life of only 450 hours. Figure 11 demonstrates that at such a low spindle strength normal flight loads, which occupy over 90% of flight time, are fatigue damaging.

1.17.3 *Accident to Sikorsky S–76A at Macae-Rio, Brazil on 20 March 1980*

The helicopter, which was being operated in support of the Brazilian off-shore oil industry, crashed into the sea shortly after taking-off from an oil production platform. The occupants, twelve passengers and two crew members, were killed.

The accident was investigated by the Brazilian Authorities with the participation of Sikorsky Aircraft. The report concluded that the accident was caused by the failure, in fatigue, of a main rotor blade spindle/cuff assembly as a result of migration of the main rotor head 'shear' bearing inner race. The increased bearing clearance produced by the displaced inner race led to abnormally high bending loads being applied to the spindle/cuff assembly. The fatigue fracture occurred at a position some 25 mm from the inboard end of the spindle. This was coincident with the first engaged thread of the blade retention nut.

As a result of this accident on 21 April 1980 Sikorsky Aircraft issued Alert Service Bulletin 76–65–13 which called for inspections to confirm the position of the 'shear' bearing inner race and provided instructions for the installation of a 'Ty-Rap' retainer to prevent excessive displacement of the inner race. This Bulletin was followed by 76–65–13A which additionally called for a one-time crack inspection of the threaded end of the spindle.

On 19 August 1980 Sikorsky Aircraft submitted Customer Service Bulletin 76–65–15 to the Federal Aviation Administration (FAA) for approval. This document was entitled 'Main Rotor Spindle Assemblies Inspection of Elastomeric Bearings for Bonding Separation – Inspection of Outer Bearing Race for Wear Limits – Replacement of Bearing Inner Race 'Ty-Rap' Retainers'. Following discussions between the FAA and Sikorsky, Section 2A of the Service Bulletin (Inspection of Outer Bearing Race for Wear Limits) was deleted. It was agreed at that time that Sikorsky would submit to the FAA the results of their investigation into the effects of bearing wear on spindle loading.

As Sikorsky Aircraft were not in a position to submit the data at that time, the Customer Service Bulletin was re-submitted for FAA approval on 27 August 1980 with all reference to shear bearing inspection and wear criteria deleted. This version of Service Bulletin 76–65–15 received FAA approval and was issued to S76 operators. Significantly the original draft of this bulletin had contained an instruction that all spindles which were found to have operated with a shear bearing diametrical clearance of more than 0.020 inches were to be withdrawn from service and returned to the manufacturer. In the event, this instruction was not published until after the accident to G–BGXY.

In a letter to Sikorsky Aircraft, dated 28 September 1980, the FAA formally requested that the manufacturer submit the data to support the inspection and/or replacement criteria for the bearing outer race.

The FAA reminded the manufacturer that the submission of their work on the re-evaluation of the spindle/cuff fatigue life was still outstanding in a letter dated 5 March 1981.

At the time of the accident to G–BGXY on 12 March 1981 Sikorsky aircraft had not submitted the results of their re-evaluation of spindle/cuff fatigue life to the FAA. However, the Sikorsky analysis at that time indicated a replacement time in excess of 8,000 hours for the assumed wear rate of the 'Teflon' lining of the bearing outer race.

1.17.4 *Maintenance History and Requirements*

1.17.4.1 *G–BGXY Maintenance History*

The rotorhead assembly fitted to G–BGXY at the time of the accident, including all four blade retention assemblies, had originally been fitted to an aircraft registered G–BHBF in the same fleet. The complete rotorhead assembly was transferred to G–BGXY on the 16 December 1979 when it had completed 92 hrs 15 mins service and G–BGXY 16 hrs 46 mins, replacing the original unit which was rejected following inspection of the hub during implementation of Customer Service Bulletin 76–65–10A. The blade retention assemblies subsequently retained their positions in G–BGXY until the aircraft crashed on the 12 March 1980. The aircraft had completed 1,171 hrs 40 mins service at take-off on the accident flight and the rotorhead components 1,247 hrs 10 mins.

At the time of the accident, the spindle/cuffs (part No 76102–08001–041) were subject to a retirement time of 8,300 hours. There was no regular maintenance or inspection requirement for the spindles themselves but they had been recorded as being 'satisfactory' after being subjected to fluorescent dye penetrant crack detection during the application of Alert Service Bulletin 76–65–13A on 25 April 1980 at 397 hrs 10 mins.

Subsequent to ASB 76–65–13A and the required fitting of 'Ty-Rap' retainers to restrict the possible outboard movement of the shear bearing inner races, the bearing assemblies would have been subject to daily inspections to determine whether the inner race was present and correctly positioned. Customer Service Bulletin 76–65–15. (Inspection of the Elastomeric Bearings for Bonding Separation and Replacement of the 'Ty-Rap' Retainer with Bonded Sleeve Type Retainers), was carried out on the 30 November 1980 at 1,002 hrs 15 mins. There is no record of any of the inner races being found to have moved or to have cracked or to have been replaced. Following initial implementation of CSB–76–65–15 the bonded retainers on the blue and yellow spindles had to be rebonded at 1,097 and 1,136 aircraft hours respectively.

A 'Zone 5' inspection (at 500 hr periods) was carried out on the 2 December at 1,007 hrs 30 mins (10 hrs extension obtained) and on the 9 December 1980 the aircraft received a 12 month renewal of its Certificate of Airworthiness in the Transport Category. On the 16 January 1981 the aircraft suffered a fire, initiated by a fault in the rotor brake, which caused severe damage aft of the main gearbox, burning through the 'Kevlar' panelling of the intake plenum chamber and damaging both engines through hot gas ingestion (AIB Bulletin 3/81). In the subsequent repair the main gearbox was replaced but the complete rotorhead was retained.

Following the flight which preceded the accident flight a record was made in the technical log that 'severe stick feedback' through the Automatic Flight Control System had occurred and had been eliminated by the crew switching off the AC (alternating current) generator. A further entry in the technical log records that the generator control unit was replaced and on the page relevant to the accident flight an entry was made as follows: 'Flight/report/test required for details see form ref nos XY 157'. Form XY 157 required a 'flight test' to check 'correct operation of both channels AFCS'. Although this defect is considered later in terms of its effect on the operation of the aircraft in its public transport role, it is not considered relevant to the cause of the accident.

Three 'Acceptable Deferred Defects' were uncleared at the time of the accident but, concerning as they do the undercarriage audio warning, the co-pilot's windscreen heat and ADF, they are not considered relevant.

1.17.4.2 S76 Maintenance Requirements

The Sikorsky S–76A is maintained to a basic maintenance cycle of 500 hours. The aircraft is divided, for maintenance purposes, into 5 Zones; maintenance of one Zone being accomplished at each 100 hour interval and the whole aircraft being covered in the 500 hour cycle. Regular repetitive 100 hour inspections ('Intermediate Inspections') accompany each 'Progressive Zone Inspection'. Other inspection requirements are covered by a specified 'Preflight Check', a '15 hour/7 day Inspection' and a provision for a 'Special Inspection' which contains requirements which are incompatible with the regular maintenance cycle.

G–BGXY was maintained as with other aircraft in the same fleet to an approved schedule derived by the operator from the manufacturer's schedule. The derived functional schedule followed the same scheme of maintenance as the manufacturer's schedule with an additional 50 hour check, and referred to the appropriate operational parts of the manufacturer's Maintenance Manual. Routine amendments to the manufacturer's schedule were incorporated into the operator's schedule after engineering vetting by the operator and approval by the Civil Aviation Authority.

The maintenance records showed G–BGXY to have been maintained in general accordance with the above sequential maintenance scheme and particular aspects of the maintenance history concerning the main blade root spindles and shear bearing are considered in detail. There was a valid Certificate of Maintenance in existence for the aircraft at the time of the accident.

Initially, the manufacturer's Maintenance Schedule contained no maintenance or inspection requirements for the main blade root spindle/cuff or the shear bearing inner or outer races. This situation was modified in respect of the inner and outer races by the issue of service bulletins and by amendments to the schedule.

Before the issue of ASB 76–65–13A the Manufacturer's Maintenance Schedule had contained a provision, introduced by Temporary Revision 5–5 dated 17 May 1979, in the 'Daily Inspection' for a visual check for the presence and position of the shear bearing inner race. This requirement was in effect at the time of the accident to G–BGXY.

In Manual Revision No 7 to the Manufacturer's Maintenance Manual bearing an issue date of 11 August 1980, item No 16 was inserted into the 'Zone 5' inspection as follows:

> 'Remove main rotor spindles and inspect bearing inner and outer races for wear, and elastomeric bearing for bonding separation per Customer Service Bulletin No 76–65–15 (Latest issue)'.

No method for assessing wear in the shear bearings inner and outer races nor criteria for judging its acceptability were given in item 16 of Chapter 5 Section 20, in the procedural section, Chapter 65 Section 12, or Customer Service Bulletin 76–65–15 as issued.

The operator has stated that when Revision 7 to the Manufacturer's Maintenance Manual was received (26 October 1980) it was not incorporated into the operator's schedule in respect of item 16 of Chapter 5 Section 20. No record is available for the reasons for not incorporating the amendment but it was considered probable that as the amendment referred to a service bulletin and it was company policy to carry out such bulletins when received (the bulletin itself called for compliance within 100 flight hours) it may have been held pending consolidation into a larger amendment.

In Temporary Revision No 5–25 to the Manufacturer's Maintenance Manual (issue date 17 October 1980) item 16 was revised to delete reference to the service bulletin and to add inspection criteria for the inner and outer races as follows:

> '(d) Outside diameter of bearing inner race for wear or cracks. If any wear or cracks are found replace inner race.
>
> (e) Bearing outer race teflon liner for wear-through, extrusion or delamination. Replace outer race if any of these conditions exist'.

This revision was received by the operator on 5 January 1981. It was processed as routine manual amendment and, following approval by the CAA, was distributed for incorporation in company schedules on 8 April 1981. Up to the time of the accident the operator's schedule contained no requirement for the inspection of the shear bearing inner and outer races nor was there any other regular maintenance operation which would require sufficient disassembly of the blade retention components to open the bearing surfaces to view. However, the spindle and the inner and outer races of the shear bearing had been open to view during application of service bulletins 76–65–13A (25 April 1980 and 397 hours) and 76–65–15 (30 November 1980 and 1,002 hours) and subsequently for the rebonding of the inner race retainers on the blue blade (11 January 1981 at 1,097 hours) and the yellow blade (18 February 1981 at 1,136 hours).

1.17.5 Additional Operational Information

1.17.5.1 Carriage of passengers on flight tests

Bristow Helicopters Ltd. Operations Manual, Air tests Supplement Page 2 states:

> '6. With the exception of Power Assurance checks and Navaid/Radio tests, flight testing must not be done when passengers are being carried. If further diagnosis of an in-flight system failure is required, the passengers must be disembarked before the test flight is made. The same provision applies to post-rectification testing. If this is required, do it before embarking the passengers'.

1.17.5.2 Minimum departure standards

Bristow Helicopters Ltd. Operations Manual, Part 5, S76A Operating Procedures, states in part:

> **'SECTION MINIMUM DEPARTURE STANDARDS**
>
> 6.1 GENERAL
>
> Flights will not depart unless serviceable equipment, as required by local legislation to the scale applicable for the flight, is carried except when

dispensation has been granted to operate without certain equipment, or when the equipment concerned is an allowable deficiency in the circumstances pertaining to a particular flight.

6.2 EQUIPMENT

Itemised allowable deficiencies under particular conditions are listed below:

6.2.1 *Public Transport Role – Day VFR Single Crew*

Outbound

a. All co-pilot's instruments other than altimeter and ASI

b. One Automatic Stabilisation system

c. Attitude Indicator (Day only)

d. Emergency Flotation Equipment, over land only

e. *Undercarriage retraction facility

*Maximum airspeed with landing gear extended or partially extended is 130 KIAS (Vno – 15 kts)

Return to Base

In addition to items listed in 6.2.1 Both Automatic Stabilisation systems

*One DC Generator

*Either AC Generator OR Static Inverter

*In either event the flight duration shall be restricted to battery endurance (ie 90 minutes).

6.2.2 *Public Transport – IFR*

a. One complete AFCS (pitch, roll and yaw) (For two pilot operation only)

b. *Undercarriage retraction facility

*Maximum airspeed with landing gear extended or partially extended is 130 KIAS (Vno – 15 kts)'

1.17.5.3 Public transport flights

Article 93(6)(a) of the Air Navigation Order 1980 states in part:

'(6) (a) Subject to the provisions of this paragraph, an aircraft in flight shall for the purposes of this order be deemed to fly for the purpose of public transport –

(i) If hire or reward is given or promised for the carriage of passenger or cargo in the aircraft on that flight; or

(ii) If any passengers or cargo are carried gratuitously in the aircraft on that flight by an air transport undertaking, not being persons in the employment of the undertaking (including, in the case of a body corporate, its directors and, in the case of the British Airways Board, or the Authority, the members of the Board or the Authority respectively), persons with the authority of the Authority either making any inspection or witnessing any training, practice or test for the purposes of this Order, or cargo intended to be used by any such passengers as aforesaid, or by the undertaking.'

1.17.5.4 Practice emergency procedures

Articles 26(3) of the Air Navigation Order 1980 states:

'(3) The operator of an aircraft registered in the United Kingdom shall not permit any member of the flight crew thereof, during any flight for the purpose of the public transport of passengers, to simulate emergency manoeuvres and procedures which the operator has reason to believe will adversely affect the flight characteristics of the aircraft.'

2. Analysis

2.1 General

It is clear that the direct cause of the accident was the in-flight separation of the 'black' main rotor blade. The investigation was therefore directed towards determining how such a catastrophic failure could occur at such an early stage of the aircraft's service life.

The investigation covered the design, certification testing and maintenance requirements of the S–76A blade retention assembly and involved an extensive programme of metallurgical tests, fatigue tests and a series of in-flight measurements of spindle loading.

2.2 Design

The components that made up the blade retention assembly were certificated to a 'Safe Life' concept. This basic design and certification philosophy requires that the manufacturer demonstrate by fatigue testing that the component will not fail within the stated life.

As the safe life concept is based upon results of fatigue tests, it is essential that the design team fully understand the loading to which the component is to be subjected, in order that the design of the fatigue test rigs accurately represent service loading conditions. Inevitably, practical considerations dictate that some simplification of the loading spectrum and a breakdown of the assembly is necessary in order to conduct a meaningful fatigue test programme. However, these engineering expediencies must not affect the accurate representation of component loading.

The predominant loads experienced by the S–76A blade spindle were tensile and bending with some torsion. The tensile loads are produced by the centrifugal forces of rotation and are reacted by the blade retention nut. Bending loads are the result of blade flap and lag movements and were designed to be reacted through the dry lubricated 'shear' bearing to the conical elastomeric bearing. Torsional loads produced by blade pitch changes were designed to be reacted mainly by the elastomeric thrust pack via the splines on the blade spindle. The threaded end of the spindle was not designed to be subjected to major bending or torsional loading. However, when, as a result of wear, the clearance in the dry lubricated 'shear' bearing increased, the thread was subjected to an increasing proportion of the spindle bending loads. The post-accident flight tests also showed clearly that under normal flight loading the spindle splines were rendered ineffective and that torsional loads were carried into the elastomeric through the spindle thread and nut.

The manufacturer's use of a machined thread in such a highly loaded component as the blade spindle, was most unusual. However, at the time of the design, thread rolling, which would have given significant advantages in terms of material grain flow and enhanced fatigue properties, presented technical difficulties when applied to titanium components. These material disadvantages were thought to be catered for in the manufacturers design calculations and testing procedure. The manufacturer had some experience of machined threads in similar locations on other helicopter types. In these other applications however, the threaded assemblies had been designed with substantial pre-loading.

During the production of the titanium spindles the thread machining process produced burrs at the crest of the threads. The original deburring process used a rotating wire brush and the spindles used in the fatigue test programme had been deburred in this way. This method of deburring was changed however for the spindles supplied for the production aircraft. The new method used a rotating 'Scotchbrite' abrasive pad which, as before, was employed to remove burrs from the crests of the threads. However, the examinations during the investigation have shown that on many spindles the abrasive pad had penetrated to the sensitive thread root area producing a pattern of fine scores. The effect of this abrasive damage to the thread root is discussed later in the analysis of the metallurgical evidence.

The manufacturers selection of shear bearing material was based on the MIL-B-81819 specification tests for spherical dry lubricated bearings, there being no standardised specification tests covering dry lubricated cylindrical bearings. This method of material selection was unsatisfactory in that it could not be used to assess the materials performance in a cylindrical bearing application, particularly when the bearing was to be subjected not only to symmetrical transverse loads but also to load concentrations as a result of spindle bending.

In view of the shortcomings of the bearing material selection process the designers might have been expected to call for accelerated wear tests as part of the blade retention assemblies test programme. However, it is now clear that the designers did not fully appreciate that as bearing clearances increased the bearing loads would be concentrated at the outboard extremity of the outer race and that this would lead to a rapidly accelerating wear condition with increasing bending loads being applied to the spindle thread.

These errors in the design of such a critical component highlight the complex interaction of dynamic loading mechanism present in a helicopter rotor system. They also show the manufacturers difficulty in accurately assessing, by calculation or measurement, the loads sustained by components, particularly in areas of complex geometry. Fixed wing aircraft designs have moved away from the 'safe life' concept for critical components and now employ 'fail safe' criteria. In view of this failure and blade spindle failures on other helicopter types it would seem prudent for helicopter manufacturers to work towards 'fail safe' designs for critical dynamic components. Until such fail safe designs are produced, the certification testing of critical components must be impeccable and all assumptions made by the manufacturer concerning component loading and wear must be given the most careful examination.

2.3 Blade Retention Assembly – Certification Testing

The programme for certification of the main rotor blade retention assembly was approved and carried out in accordance with a Test Programme Plan which conformed to US Federal Airworthiness Regulation No. 29. The plan called for tests to prove the integrity and durability of the spindle/cuff and the elastomeric. The dry lubricated 'shear' bearing was not considered as a major component in so far as the testing was concerned. Despite the fact that the bearing was responsible for load transfer between the spindle and the elastomeric, the bearing was not subject to a similar programme of endurance testing.

The manufacturer had considered that the Ground-Air-Ground (GAG) cyclic loading would be the principal fatigue damaging case and had correctly judged that the likely failure mode would be a fatigue crack initiated within the spindle thread. The spindle fatigue test rig consisted of a complete retention assembly which included the elastomeric and 'shear' bearing. It was designed to apply axial and bending loads only, because torsional loads were expected to be removed by the spindle splines and hence not be a part of the thread loading mechanism. This incorrect assumption had a far reaching effect on the results of the testing. Firstly, as the post-accident flight tests proved, the splines did not remove torsional loading therefore the certification tests did not include one part of the thread loading spectrum. Secondly, and more importantly, as no rotational motion was applied to the spindle a major element in the bearing wear mechanism was not represented in the testing. Had the rig tests included spindle rotational motion then the poor wear characteristics of the Fafnir manufactured shear bearing in this application would have been revealed. Thirdly, the most important of all, the effect of increased clearance in the shear bearing on the spindle stresses in the most likely place of failure was never considered.

In the absence of an accelerated wear test for the 'shear' bearing the manufacturer relied on the 'tear down' inspection of the flight test fleet leader aircraft at 1,000 hours for an assessment of bearing durability. The results of this inspection apparently revealed that 'shear' bearing wear was 'within tolerances' (presumably manufacturing tolerances as no wear tolerances are quoted for the bearing). This statement does not equate with the experience gained as a result of the post accident dimensional checks and it seems likely that the fleet leader aircraft was only subjected to a visual inspection for condition at that time.

One further aspect of the certification tests rendered the results less than representative of the blade retention assembly in service. All six spindles used in the certification testing has been deburred with a rotating wire brush while those on the production aircraft had been subjected to the 'Scotchbrite' deburring process. As a result of the post-accident research into the metallurgical effects of 'Scotchbrite' scoring it is now clear that the spindles fitted to production aircraft were likely to exhibit a lower fatigue strength than the test specimens.

The certification process is meant to ensure that an aircraft does not enter service with major flaws in its design. To achieve this aim the testing programme must represent as closely as possible the loading conditions to be met in service. In the case in question, as with most cases of structural failure in service, it has been shown that the testing was not representative and hence did not identify a major design shortcoming. The errors in the Federal Aviation Administration (FAA) certification programme were not identified by the CAA when the S76 was presented for certification in the United Kingdom (UK). At that time the helicopter was subject to a further design study as part of the Civil Aviation Authorities (CAA) validation of the original FAA certification. The concept of UK validation of foreign certificated aircraft, is based on the understanding that the CAA will direct its technical investigation into those areas where the foreign and UK airworthiness requirements differ. Additionally any unusual design feature would normally be the subject of a more detailed design investigation. In the case of the S76 however, despite the fact that it was the first UK certification of a helicopter rotor system employing elastomeric bearings in this configuration, and was without doubt an 'unusual design feature', the rotorhead was not the subject of any additional design investigation during the CAA validation process.

The accident to the Sikorsky S–76A at Macae-Rio, Brazil, approximately one year before the subject accident, highlighted the catastrophic efforts of 'shear' bearing clearance on the spindle thread loading. The manufacturer's reaction after the fracture analysis on the Brazilian accident spindle had been completed, was to submit a draft Customer Service Bulletin for FAA approval. This original version of the Bulletin included instructions for a dimensional check of the 'shear' bearing outer race for wear and the return to the manufacturer of any spindles which had been operating with a bearing clearance of more than

0.020 inches. This version of the Bulletin was witheld and following discussions between FAA and Sikorsky, Service Bulletin 76-65-15 was issued with all reference to the shear bearing clearances deleted. The FAA had asked that Sikorsky formally submit a spindle fatigue life re-evaluation which was to include the effect of bearing wear on spindle life. It is clear that the FAA expected an early response from the manufacturer but despite a formal request dated 28 September 1980 and a rather terse reminder dated 5 March 1981, Sikorsky Aircraft had not submitted this data at the time of the accident on 12 March 1981.

The consequences of this delay are now clear. Had the instructions for bearing wear assessment contained in the draft bulletin, been implemented, then the manufacturer and airworthiness authorities would have been alerted to the adverse wear characteristics of the Fafnir manufactured 'shear' bearing. This information would certainly have caused the manufacturer and airworthiness authorities to call for the replacement of worn outer races and would have led to the introduction of inspections and wear limits for the bearings. Such action could have prevented the accident to G-BGXY on 12 March 1981.

2.4 Shear Bearing Wear

The results of the S–76A fleet dimensional checks conducted immediately after the accident and presented at Figure 7 show a clear difference in wear behaviour between the two manufacturers versions of the shear bearing. In particular the data shows that the Fafnir bearings exhibited a more rapid rate of wear than the Kahr equivalent. There was insufficient data to determine the wear characteristics of the Fafnir bearings as a function of flying hours. However, it is a known feature of teflon dry lubricated bearings for there to be three distinct phases of wear; an initial 'bedding in' phase of rapid but limited wear, a long period of low wear rate representing the bearings useful life and a final peiod of very rapid wear producing wear-through of the remaining bearing material in a very short time. It is possible therefore that for most of their time in service the existent bearing clearance in the Fafnir bearings was less than 0.020 inches with the final rapid increase occurring shortly before the accident.

No special factor was identified which might account for the markedly worse wear seen in the Fafnir bearings in G-BGXY and this, together with the fact that the single Kahr bearing exhibited wear which was within the scatter of others shown in Figure 7, strongly suggests that the Fafnir bearings had simply worn out following a normal, though rapid wear process as described above. Further, the wear pattern seen in the bearings indicates that the rapid wear rate was produced by a combination of load concentration due to the imposed bending loads on the spindle and spindle rotational oscillation, conditions for which the bearings had not been assessed.

2.5 Metallurgical Examination and Fracture Analysis

From the flight test results it was known that the threaded portion of the spindle was subjected to non-design torsional loads and excessive bending loads in addition to the known axial loads, all of complex variation and phasing.

Consideration was therefore given to the interpretation of the fracture evidence with a view to determining what factors had been effective in the crack's initiation and development.

The development of the fracture generally in the plane of vertical bending and its position at the first engaged thread is consistent with the orientation of the major cyclic flight loading and with a known position of stress concentration; this was the mode and position of fatigue failure anticipated by the manufacturer. However, the fact that initiation was multiple and in a bending plane between 30 and 50 degrees from the plane of failure points to further factors being involved in the initiation process.

The subsequent development of the individual areas of fatigue offers evidence which might indicate the nature of the loads which were effective in creating fatigue damage. The asymmetric development of the principal area of fatigue could be indicative of a torsional loading component. Alternatively, it could be that, while local stress concentration was a dominant factor in the initiation of the crack, which therefore began in a plane other than that of maximum loading, as the crack developed and that factor became ineffective the crack front developed more quickly on the side nearer the plane of maximum load and hence turned, as seen here, towards that plane.

The angle of the plane which the principal fracture adopted within the section was also considered as a feature which might help identify the loads causing fatigue damage. Such an angled development of a fatigue failure might indicate torsion but in this case the angle was in the wrong direction to be consistent with a 'blade pitch up' torsional load, the maximum torsional load. This, together with the flight test results which appear to indicate that cyclic torsion was more or less out of phase with flapwise bending, suggests, therefore, that the fracture plane angle was not the result of a torsional influence. However, the flapwise and edgewise, bending loads had complex waveforms and their interaction with the torsional load, which also had a residual steady component, is not amenable to a complete analytical understanding given present knowledge of the fatigue mechanism. It would seem prudent therefore in future life assessments of the spindle to assume torsion to be fully fatigue damaging in combination with bending and axial cyclic loads.

A stress concentration factor, in addition to that of the thread notch itself, was of course identified at the principal origin. It seems reasonable to accept that the score-mark was caused by the 'Scotchbrite' process, a process demonstrated by the small scale coupon fatigue tests to have a deleterious effect on spindle fatigue strength. These tests showed that the 'Scotchbrite' process when applied to notched coupons reduced the fatigue strength by an average of 26% and greatly inceased its variability in a given sample. Coupons that had been stress-relieved from both the as-machined and the Scotchbrited condition showed a greater mean reduction in strength but less variability. The stress-relieved results effectively occupied the lower bound of the 'Scotchbrite' data.

The manufacturer interpreted these results as indicating, because of the low strengths from the stress-relieved samples, that the original thread machining process had produced a surface condition with residual compressive stress which the 'Scotchbrite' treatment had penetrated. Assuming this interpretation to be correct it was also conceivable that the deleterious effect of 'Scotchbrite' would be a very variable effect giving the observed increase in scatter.

The restricted sample size and the observed scatter of the full scale spindle tests limited the confidence with which mean values could be established and, therefore, changes in strength assessed. In general, however, the results do appear to be consistent with the effects seen in the small scale coupon tests. The 'Scotchbrite' treated spindles showed a marked strength reduction and the stress-relieved spindles gave strengths below the range of Scotchbrited spindles. These results taken with the small scale coupon results led the manufacturer to believe that, for a larger sample size of Scotchbrited spindles, the weakest spindle would have a fatigue strength slightly below the weakest of the stress relieved spindles tested.

Expert metallurgical opinion was divided on what sequence to attribute to the multiple origins. One interpretation was that the origins other than the primary may have been secondary in time; re-initiations in the thread root as the angled penetration of the crack carried the crack tips up the threaded flank. Slower development in the aft direction would perhaps permit re-initiation ahead of the advancing crack front, the rate of advance being too high in the forward direction towards the plane of maximum load to allow time for re-initiation. In this interpretation the stress-concentration due to the 'Scotchbrite' score need have been the only additional factor.

Another interpretation of the sequence and development of these features was that there might have been a wider area of stress concentration due to uneven circumferential load transfer between the spindle and nut threads giving multiple origin initiation variously at 'Scotchbrite' scores or other surface defects. As the spindle thread start position and nut positions were variable some spindles would be weaker, under this interpretation than others, dependent on the alignment of thread engagement with the plane of maximum loading. Attempts by the manufacturer to elucidate this problem did not produce results to show it to be a large or well defined effect. It is however, an aspect of screw thread detailed design which is difficult to assess experimentally, as the installation of instrumentation to measure local stresses itself alters those stresses.

In summary, therefore, the fractographic evidence can be considered to support the hypothesis of the principal fatigue area being the first in time, initiating at a local stress-raising feature ('Scotchbrite' score) and subsequently developing into the place of maximum load. This evidence, therefore, while being a matter of interpretation and not wholly conclusive on its own, is consistent with the sequence of failure postulated from the other evidence on shear bearing wear, high flight loading and the deleterious effect of the deburring process.

2.6 Maintenance Requirements

Apart from the 'one-time' examination detailed in ASB 76-65-13A, the operator, up to the time of the accident to G-BGXY, was not required to examine the blade root spindles in the critical area of the retention thread. Under the procedures and practices by which the spindle was certificated as a lifed item such inspection would not normally be necessary.

The circumstances surrounding the maintenance of the second significant component involved in the failure of the blade root spindle, the dry-lubricated 'shear' bearing is more complicated as some requirement for its inspection did exist before the time of the accident. It is the maintenance requirement concerning the outer race which is of principal interest as inner race wear contributed only a small proportion of the lateral play which was responsible for increasing spindle loads. There were no recorded problems with cracking or movement of the inner races as had been the case in the spindle failure in PT-HKB at Macae, Brazil, but maintenance and inspection of the inner races is of interest in that their surface condition, by the time of the accident, could have given a visual indication of a high wear condition in the bearings if the significance of their polishing and 'phonographic' grooving had been known.

Up to the time of the accident there was no requirement in the documents to which G-BGXY was being maintained i.e., the Operator's Schedule, the Manufacturer's Maintenance Manual to which it referred or in the applicable service bulletins, for the examination of the surface condition of the inner or outer races nor, of course, were there any criteria given by which their condition could be judged nor any indication of the critical nature of any wear in the bearing. The applicable daily inspection of the inner race did not involve any assessment of wear.

It can only be a matter of surmise as to what the bearing conditions were at the times at which they were open to inspection. From their condition after the accident it would appear that all outer races, barring possibly, the blue bearing, would have had a complete surface coating of 'Teflon'. Though, at the time of the accident the blue bearing had suffered, locally, complete wear-through of the 'Teflon' layer and there had been metal-to-metal contact, it cannot be determined for how long that condition had existed. It seems probable that the conditions which, in retrospect, can be seen as indicative of a high wear rate, polishing and 'phonograph' grooving of the two surfaces and the localised occurrences of these effects, would have been in evidence when the bearings were opened up (SB 76-65-15 at 1,002 hours and subsequently for rebonding on blue and yellow spindles). However, even if item 16 of Chapter 5 section 20 of the Maintenance Manual had been available in the operator's schedule they might well have been deemed acceptable as, assuming that a full coating of 'Teflon' existed on the outer race, as was certainly the case with the black bearing, neither wear-through, extrusion nor delamination would have been evident and the high polish and grooving need not have been considered suspect against those criteria. Again, this was a novel application for this type of bearing so that maintenance personnel could not be expected to have relevant experience from which they could identify a high wear condition nor had they been alerted to the critical nature of wear in that location. It is a point to note, here, that, with a smaller degree of dimensional wear, the Kahr bearing gave a more marked visual indication of wear because of colour differences between the outer and inner layers of the 'Teflon' coating.

In any case, without explicit dimensional criteria for wear, an inspection of the bearings could not be effective in preventing load increases in the spindle and no such criteria were made available either in the operator's instructions or the manufacturer's before the accident to G-BGXY.

The elapsed time from the first formulation of the inspections for the outer race (Amendment No. 7 issue date 11 August 1980 subsequently amended by Temporary Revision 5-25 issued 17 October 1980) to the final availability of such inspections to the maintenance staff on 8 April 1981 was eight months. There was, however, no apparent urgency in the method of issue by the manufacturer as they were issued as routine manual amendments, each taking two months from date of issue to reach the operator.

Item 16 as first issued was ambiguous and inconsistent in its wording. It may be read straightforwardly, as referring the maintenance engineer to Customer Service Bulletin 76-65-15 for inspection procedures and requirements for the inner and outer races and the elastomeric bearings, thereby also making the bulletin repetitive within the normal maintenance schedule. Read in this way it would be consistent with bulletin 76-65-15 as originally drafted.

However, if it were read in conjunction with bulletin 76-65-15 as issued, where there was no reference to shear bearing wear, it might be read as an instruction to inspect the shear bearing for wear and to refer to bulletin 76-65-15 for the inspection procedure for the elastomeric bearings only. Read in this way it would be inadequate as an instruction as, again, no criteria were given for assessing wear and its acceptability and, inevitably, there would be some wear present in the bearings.

Item 16, as originally presented was, therefore, confusing. It could be argued that the decision not to incorporate item 16 into the operator's manual in the first instance might have lost the formal requirement for the bearing condition to be examined (assuming the second interpretation of item 16) at the last zone 5 inspection on G-BGXY but there would have been no criteria, dimensional or merely qualitative, by which to judge the bearings acceptability and such inspection would not have provided an adequate safeguard for the spindle.

The modified and more explicit version of item 16 introduced in Temporary Amendment 5-25 (issue date 17 October 1980) was still inadequate from the point of view of limiting spindle bending loads. As it was a routine manual amendment it suffered a delay in its availability to maintenance staff beyond what would otherwise have been the case because of the existence of a separate operator's schedule and the need for the amendment to be vetted and approved for inclusion in that manual. The existence of a separate schedule does entail additional delays in the introduction of maintenance changes but it does have offsetting advantages where a major operator is itself approved for design and modification and the aircraft is certificated under an authority other than the original. There also exists a system, through Alert Service Bulletins, for a rapid change in maintenance procedures where the manufacturer considers it necessary. Therefore, though it could be argued that the operators procedures caused a delay in implementation of a possibly relevant maintenance action these procedures were valid in the context of the overall maintenance situation and the operator did not possess the design or service knowledge by which to give the modification any more priority than that given to it by the manufacturer.

It appears probable that the confusion evident in the maintenance inspection of the outer race as first introduced was as a result of the vicissitudes suffered by Bulletin 76-65-15 before it was approved and published and that item 16, drafted to be consistent with the original version of Bulletin 76-65-15, was, presumably through oversight, not re-drafted when Bulletin 76–65–15 was modified.

2.7 Operational Aspects

The provisions of Article 93(6) (a) (ii) of the Air Navigation Order 1980 (the ANO) mean that the flight, notwithstanding that it was planned and flown as a training flight, automatically became one for the purposes of public transport when passengers were accepted and carried. From this it follows that in performing a number of reject landings at the start of the flight the Captain apparently infringed Article 26(3) of the ANO. There was no evidence available as to whether or not the Commander appreciated the combined effect of these two articles of the ANO.

It is also not known whether the commander, in addition to seeking the agreement of the Line Supervisor to departing with an unserviceable AC generator, consulted the aircraft copy of the Company Operations Manual to refresh his memory on the Minimum Departure Standards laid down therein. It is clear from these that an AC generator is not an allowable deficiency on an outbound public transport flight, and so once it had been determined that the unserviceablity remained the flight should have been cancelled or the passengers disembarked.

A further point concerns the carriage of passengers on a flight authorised as a test flight. Once the aircraft's technical log was stamped to require a test flight following the rectification work, the planned flight took on the dual nature of being both test and a training flight. The Company Operations Manual specifically prohibited the carriage of passengers on all flight tests with the exception of power assurance checks and navaid/ radio tests, and so passengers should not have been accepted and boarded for the flight. In the event it is arguable whether the flight was in fact a test flight since the component to be tested was found to be still unserviceable before the aircraft left the dispersal area, and it is not known whether the Captain intended to, or did, test it again after becoming airborne.

3. Conclusions

(a) Findings

(i) The helicopter had valid certificates of airworthiness, maintenance and registration and had been maintained to an approved maintenance schedule.

(ii) The flight crew were properly licensed and adequately experienced to carry out the flight.

(iii) The aircraft's loading and centre of gravity were within the prescribed limits for the flight.

(iv) The aircraft broke-up in level flight following detachment of the main rotor blade colour coded 'black'.

(v) The 'black' blade detached through the failure in fatigue of the threaded portion of the blade spindle/cuff at the position of its engagement in the blade retention nut.

(vi) The dry lubricated 'Shear' bearings within the blade retention assemblies had suffered a high degree of wear as a result of load concentrations on the bearing surface.

(vii) A high degree of wear was detected in the shear bearings of other S-76A helicopters and, as with G-BGXY, was more marked in the bearings manufactured by one of the two proprietary suppliers than the other.

(viii) The 'shear' bearing wear significantly increased the spindle bending loads.

(ix) The 'shear' bearing wear experienced in service was not detected during pre-certification development flying of prototype aircraft.

(x) The certification rig testing of the blade retention assembly did not subject the 'shear' bearing to a representative wear process.

(xi) The deburring process used on the spindle threads of production spindles reduced the spindle fatigue strength when the process penetrated to the thread root.

(xii) The fatigue rig testing carried out to determine the service retirement time for the spindle was unrepresentative of the actual service conditions on two counts:

(a) No torsional loads were applied as none were anticipated in the expected, and actual, failure plane in the spindle thread.

(b) Deburring processes which could affect the sensitive thread root area differed between the test spindles and those fitted to aircraft in service.

(xiii) Torsional spindle loads were transferred to the elastomeric thrust bearing through the spindle thread and not through the purpose designed spline.

(xiv) No flight or ground operating condition was found which subjected the blade retention assembly to fatigue loadings more severe than those assumed during certification.

(xv) The fatigue failure of the black blade spindle on G-BGXY at 1,247 hours was explicable in terms of the factors considered in this report.

(xvi) The CAA's examination of the S76 rotor system, conducted as part of the United Kingdom validation of the FAA certification, was not sufficiently detailed to enable the shortcomings in the design and certification testing to be revealed.

(xvii) The decision to withold publication of the original submission of Customer Service Bulletin 76-65-15 after the S–76A spindle failure in Brazil, prevented an early recognition of the high wear rate associated with the 'shear' bearing outer race.

(xviii) The helicopter manufacturers dilatory response to the FAA request for a re-evaluation of the spindle fatigue life following the accident to PT-HKB in Brazil prevented a full appreciation by the Administration of the increased spindle loading associated with shear bearing wear.

(xix) Neither the inspections detailed in the approved maintenance schedule nor the Service Bulletins issued after the accident to PT-HKB in Brazil, were adequate to detect the high wear in the spindle 'shear' bearings which combined with the reduction in strength caused by the deburring process was responsible for the spindle failure.

(xx) The aircraft commander was in breach of Article 26(3) of the Air Navigation Order in carrying out rejected take-off manoeuvres when carrying passengers and in breach of the company operational procedures in carrying passengers on a flight authorised as a test flight.

(b) Cause

The accident was caused by the in-flight separation of the main rotor blade coded 'black' as a result of a failure in fatigue of the blade spindle. Shortcomings in the design assessment, certification testing and control of manufacturing processes were contributory factors.

4. Safety Recommendations

It is recommended that:

4.1 Aircraft manufacturers and Airworthiness Authorities consider the effects of service wear on the loading of critical components during the design and certification processes.

4.2 Airworthiness Authorities seriously consider a requirement that critical components in helicopter rotor systems be designed to 'fail safe' criteria.

K P R Smart
Inspector of Accidents
Accidents Investigation Branch
Department of Transport

March 1984

Bas 257009/Dd 737610 C7 6/84

ISBN 0 11 550650 0